Acritarchs from the Duolbagáisá Formation (Cambrian Series 2–Miaolingian) on the Digermulen Peninsula, Finnmark, Arctic Norway: towards a high-resolution Cambrian chronostratigraphy

Teodoro Palacios[1], Anette E. S. Högström[2], Jan Ove R. Ebbestad[3], Heda Agić[4], Magne Høyberget[5], Sören Jensen[1], Guido Meinhold[6,7] and Wendy L. Taylor[8]

[1]Área de Paleontología, Facultad de Ciencias, Universidad de Extremadura, Avenida de Física s/n, 06006 Badajoz, Spain;

[2]Arctic University Museum of Norway, UiT the Arctic University of Norway, 9037 Tromsø, Norway;

[3]Museum of Evolution, Uppsala University, Norbyvägen 16, 752 36 Uppsala, Sweden;

[4]Department of Earth Sciences, Uppsala University, 752 36 Uppsala, Sweden; Department of Earth Science, University of California at Santa Barbara, Santa Barbara, CA 93106, USA;

[5]Magne Høyberget, Rennesveien 14, 4513 Mandal, Norway;

[6]Department of Sedimentology & Environmental Geology, Geoscience Center, University of Göttingen, Goldschmidtstraße 3, 37077 Göttingen, Germany;

[7]School of Geography, Geology and the Environment, Keele University, Keele, Staffordshire, ST5 5BG, UK and

[8]Department of Geological Sciences, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa

Author for correspondence:

Teodoro Palacios, Email: medrano@unex.es

Abstract

New information on acritarchs from the Duolbagáisá Formation, Digermulen Peninsula, Arctic Norway, enable recognition of the three Cambrian Series 2 acritarch-based zones: the *Skiagia ornata–Fimbriaglomerella membranacea*, *Heliosphaeridium dissimilare–Skiagia ciliosa* and *Volkovia dentifera–Liepaina plana* Assemblage zones. Acritarchs of the *Skiagia ornata–Fimbriaglomerella membranacea* Zone (Cambrian Stage 3) appear near the base of the unit, close to an undetermined trilobite. In the upper member of the Duolbagáisá Formation, in levels with *Kjerulfia* n. sp. and *Elliptocephala* n. sp., appears an assemblage with abundant *Skiagia ciliosa*, indicative of the *Heliosphaeridium dissimilare–Skiagia ciliosa* Zone. A few meters higher appear *Liepaina plana*, *Heliosphaeridium notatum* and *Retisphaeridium dichamerum,* which indicate the *Volkovia dentifera–Liepaina plana* Zone (Cambrian Stage 4). The transition between the Duolbagáisá Formation and the overlying Kistedalen Formation is marked by the appearance of *Comasphaeridium longispinosum*, *Multiplicisphaeridium llynensis* and *Eliasum llaniscum,* diagnostic of the Miaolingian Series. This coincides with the disappearance of *Skiagia;* occurrences of *Skiagia* in Miaolingian strata consist of reworked material related to the Hawke Bay regression at the Cambrian Stage 4–Wuliuan transition. The absence of *Skiagia* in higher levels of the Duolbagáisá Formation and Kistedalen Formation suggests that no unconformity formed during the Hawke Bay regression in this area. The chronostratigraphical significance of the *Skiagia ornata–Fimbriaglomerella membranacea, Heliosphaeridium dissimilare–Skiagia ciliosa*, and *Volkovia dentifera–Liepaina plana* zones is critically analysed. Correlation of the Duolbagáisá Formation with peri-Gondwanan terrains of Avalonia and Iberia is established. The Digermulen Peninsula has great potential as a reference section for establishing a Cambrian chronostratigraphy based on acritarchs.

Keywords: acritarchs; Cambrian; chronostratigraphy; Hawke Bay regression; Norway; organic-walled microfossils

1. Introduction

The Digermulen Peninsula (Fig. 1) in Arctic Norway includes one of the most complete successions of Cryogenian–Lower Ordovician strata in the world with an important record of diverse organic-walled microfossils (Vidal, 1981; Welsch, 1986; Högström *et al.* 2013; Palacios *et al.* 2015, 2017b) well suited for establishing a high-resolution Cambrian chronostratigraphy. Acritarchs represent a polyphyletic group of form-taxa, most of which represent organic-walled cysts. These fossils are essential for Cambrian biochronology as they were generally cosmopolitan in distribution and can often be extracted in great numbers from fine-grained siliciclastic rock deposited under marine conditions.

Cambrian acritarch zonations were first established in the western part of the East European Platform (western Russia, the Baltic States, Ukraine, Belarus, and Poland). The stratigraphical distribution was recognized within 'horizons' of the lower Cambrian comprising in stratigraphically ascending order the Rovno, Lontova, Talsy, Vergale, and Rausve horizons (Volkova *et al.* 1983). A comparable formal zonation based on studies of numerous drillcores was established in south-eastern Poland (Moczydłowska, 1991), comprising in stratigraphically ascending order the *Asteridium tornatum–Comasphaeridium velvetum*, *Skiagia ornata–Fimbriaglomerella membranacea*, *Heliosphaeridum dissilimilare–Skiagia ciliosa* and *Volkovia dentifera–Liepaina plana* Assemblage zones (in the following given in abbreviated form).

The *Asteridium–Comasphaeridium* Zone and the Rovno and Lontova horizons have been correlated with the Terreneuvian Series, with an approximate duration of 20 Ma (Cohen *et al*. 2013). The Rovno horizon is approximately equivalent to the Fortunian Stage, and is characterized by morphologically simple acritarchs (leiosphaerids) and filamentous sheaths. The Lontova Horizon, equivalent to the *Asteridium–Comasphaeridium* Zone, corresponds to the Fortunian and Stage 2 in part.

However, the correlation of these zones outside their original source areas is sometimes problematic. On the Digermulen Peninsula, as well as in sections on Newfoundland and in New Brunswick, Canada, the name-bearing taxa of the *Asteridium–Comasphaeridium* Zone are absent from basal Fortunian strata, which instead are characterized by acritarchs lacking processes (*Leiosphaeridia* spp., *Granomarginata squamacea* and *G*. *prima)* (Palacios *et al.* 2011, 2017b, 2018; Högström *et al.* 2013). The first assemblages in well-exposed successions with a good record of organic-walled microfossils, including those diagnostic of the *Asteridium–Comasphaeridium* Zone, have been located in New Brunswick at levels dated to 531 Ma (Palacios *et al.* 2011) and on Newfoundland at levels above the *Watsonella crosbyi* Zone (Palacios *et al.* 2018). Following Palacios *et al*. (2018) and herein we therefore identify the *Asteridium–Comasphaeridium* Zone only when the index taxa are present. Low diversity Fortunian assemblages dominated by *Granomarginata*, that were previously included in this zone (i.e. Moczydłowska, 1991), are instead included in an assemblage that encompass the *Granomarginata* Zone (Palacios *et al*. 2018), and a lower assemblage dominated by leiosphaerids.

The succeeding acritarch zones, the *Skiagia–Fimbriaglomerella*, *Heliosphaeridium–Skiagia* and *Volkovia–Liepaina* zones*,* allow a more detailed division of Cambrian Series 2 (approximate duration of 12 Ma, Cohen *et al*. 2013) compared to that of the Terreneuvian (approximate duration of 20 Ma, Cohen *et al*. 2013). On Baltica the base of the *Skiagia–Fimbriaglomerella* Zone approximates the position of the earliest trilobites of the *Schmidtiellus* Zone (Moczydłowska, 1991). More broadly, *Skiagia* has been suggested to have a global first appearance close to the appearance of trilobites and to the base of the yet undefined Cambrian Series 2 (Moczydłowska & Zang, 2006). The

appearance of *Skiagia* coincides with a substantial increase in the diversity of phytoplankton that signals the onset of the Cambrian phytoplankton radiation (e.g. Vidal & Moczydłowska-Vidal, 1997; Moczydłowska, 2011; Palacios *et al*. 2018).

In the present paper, the first data on acritarchs from the Duolbagáisá Formation on the Digermulen Peninsula is presented, establishing for the first time an acritarch-based chronostratigraphic framework for this part of Baltica. A critical analysis of current acritarch zonations and their potential for chronostratigraphy of Cambrian Series 2 is made.

2. Geological setting

The Digermulen Peninsula, Arctic Norway (Fig. 1a), includes a thick parautochthonous succession of Cryogenian–Lower Ordovician strata (Føyn, 1937; Banks *et al.* 1971) divided into the Cryogenian–Terreneuvian Vestertana Group and the Cambrian Series 2–Lower Ordovician Digermulen Group (Reading, 1965) (Fig. 1b).

The basal formations of the Vestertana Group include, in ascending order, the Cryogenian glaciogenic diamictites of the Smalfjorden Formation, the Nyborg Formation, and the Ediacaran diamictite of the Mortensnes Formation correlated with the Gaskiers glaciation of Newfoundland (Rice *et al*. 2011; *c.* 580 Ma, Pu *et al*. 2016). The Nyborg and Mortensnes formations contain organic-walled microfossil assemblages of low diversity (Vidal, 1981), with the Nyborg Formation notable for an organically-preserved multicellular eukaryote (Agić *et al.* 2019). The presence of Doushantou–Pertataka-type acritarchs in the Nyborg Formation points to an Ediacaran age and corroborates other lines of evidence for a Gaskiers-equivalent age for the Mortensnes glacial deposits (Agić *et al.* 2018). The succeeding Stáhpogieddi Formation comprises the lower quartzitic sandstones (Lillevannet Member), blue-green and red-violet mudrock (Indreelva Member) and the Manndrapselva Member (Banks *et al*. 1971), the latter with a basal quartzitic sandstone followed by two coarsening upward successions of greywacke sandstone and mudstone and sandstone. The Ediacaran–Cambrian transition is recognized within the Manndrapselva Member on the basis of ichnofossils (i.e. *Treptichnus pedum*) and organic-walled microfossils (Högström *et al*. 2013; Palacios *et al*. 2017b; Jensen *et al*. 2018).

The lower part of the Breidvika Formation, the uppermost unit of the Vestertana Group, yields *Platysolenites antiquissimus* and *Rusophycus* sp., and acritarchs diagnostic of the *Asteridium–Comasphaeridium* Zone (Vidal, 1981; Högström *et al*. 2013; Palacios *et al*. 2017b). Banks (1970) reported *Platysolenites antiquissimus* from the lower part of the formation, but McIlroy *et al*. (2001) documented specimens only from the upper part.

The Digermulen Group is made up of three formations. At the base, the Duolbagáisá Formation (Reading, 1965; Banks *et al*. 1971) includes two members. The Lower Member is well exposed along the coast to the NE of Breidvika Valley, in the Siskkit Vuorrevággi section (Fig. 1b) where it consists of 256 m of siltstone, mudstone and quartzitic sandstone (Fig. 2). This member contains abundant trace fossils (Banks, 1970; McIlroy & Brasier, 2017), an unidentified trilobite (Ebbestad *et al*. 2018), and near the base of the member, the enigmatic agglutinated tube-shaped fossil *Volborthella tenuis* (Crimes & McIlroy, 1999; McIlroy & Brasier, 2017) which is taken to mark a point at around the base of Cambrian Series 2 (McIlroy & Brasier, 2017). The Upper Member of the Duolbagáisá Formation is well exposed in the Breidvika Valley (Figs 1, 3). Here it consists of 382 m of quartzitic sandstone with minor intercalations of fine-grained sandstone, siltstone and mudstone that have their maximum thickness in the middle part, where trilobites occur, including *Kjerulfia* n. sp*., Elliptocephala* n. sp. and rare ellipsocephalids (Nikolaisen & Henningsmoen, 1990; Ebbestad *et al*. 2017, 2018).

The overlying Kistedalen Formation contains trilobites and acritarchs of Miaolingian–Furongian age (Welsch, 1986; Nikolaisen & Henningsmoen, 1985, 1990; Palacios *et al*. 2015). The boundary between the Duolbagáisá and Kistedalen formations has been suggested to approximate the Cambrian Series 2–Miaolingian boundary (Nielsen & Schovsbo 2015; but see below). Nielsen & Schovsbo (2015) considered the possibility that the upper sandstone-dominated part of the Duolbagáisá Formation represents lowstand deposits related to the Hawke Bay regression, which is concurred herein. The Kistedalen Formation is divided into five members, K1–K5. The lower member, consisting of sandstone with interbedded mudstone and siltstone (K1) yields Miaolingian trilobites near the base (*Eccaparadoxides* cf. *pusillus*, *Ellipsocephalus* cf. *hoffi*, *Hydrocephalus* cf. *carens*), of uncertain zonal assignment, but Nikolaisen & Henningsmoen (1990, p. 77) suggested the *Eccaparadoxides insularis* Zone. The K2 member consists of mudstone intercalated with dark grey to black sandstone at the top, and yields abundant acritarchs (Welsch, 1986; Palacios *et al*. 2015). The K3 member ‘black quartzite member’ and the K4 (black shale) yields Furongian acritarchs (Welsch, 1986). The formation culminates with a massive sandstone (K5). The Digermulen Group terminates with the Bearalgáisá Formation, consisting mainly of shale and sandstone in the lower part and sandstone and minor shale in the upper part and yields Tremadocian trilobites and acritarchs (Nikolaisen & Henningsmoen, 1985; Welsch, 1986).

3. Material and methods

This study is based on shale and siltstone samples from the Duolbagáisá Formation collected by the authors between 2011 and 2017. A total of 55 samples (Figs 2, 3) have been processed, mainly of shales with colours ranging from green and light grey to olive green and dark grey. Stratigraphic levels and quantitative distribution of the identified acritarch species in positive samples are shown in Figures 2 and 3. Samples of *c.* 50 g were treated with standard

palynological methods, mounted on glass slides with Petropoxy 154 resin, and studied under transmitted light with a Zeiss Axio Imaginer M1 microscope with a computerized AxioCam HRc microscope camera. The positive samples contain relatively well-preserved (brown to dark brown, TAI 3–4 *sensu* Hayes *et al*. 1983) acritarchs. Studied and illustrated material (Figs 4–7, 9, 10) is stored with the palaeontological collection of the Arctic University Museum of Norway, prefix TSGf, with the exception of comparable material from the Hanford Brook Formation, New Brunswick, Brigus Formation, Newfoundland and Lancara and Vallehondo formations, Spain (Fig. 8), which is reposited in the collections of Área de Paleontología of the Universidad de Extremadura, Badajoz. Museum numbers are referred to in the figure captions, which also provide sample numbers and England finder coordinates.

4. Acritarch assemblages from the Duolbagáisá Formation

The distribution of fossiliferous samples through the Duolbagáisá Formation has allowed recognition of the three Cambrian Series 2 acritarch assemblage zones; the *Skiagia–Fimbriaglomerella* Zone (Stage 3), *Heliosphaeridium–Skiagia* Zone (Stages 3–4) and *Volkovia–Liepaina* Zone (Stage 4). *Comasphaeridium longispinosum, Eliasum llaniscum*, and *Multiplicisphaeridium llynensis* at the transition between the Duolbagáisá–Kistedalen formations, indicate the beginning of the Wuliuan stage. In the following section, we present a critical analysis of these assemblages and their chronostratigraphic implications.

4.a. Skiagia ornata–Fimbriaglomerella membranacea Zone

The first diagnostic acritarchs, *Skiagia orbiculare* (Fig. 4a) and *Skiagia* sp., occur in the lower part of the Lower Member of the Duolbagáisá Formation (Fig. 2). Acritarchs in the middle-upper part of the Lower Member are more diverse and abundant, including *Skiagia ornata* (Fig. 4d, e), *S. orbiculare* (Fig.4b), *S. compressa* (Fig. 4f, g), *S. brevispinosa* (Fig. 4c), *Fimbriaglomerella membranacea* (Fig. 5a), *Comasphaeridium brachyspinosum* (Fig. 5b) and *Lophosphaeridium dubium* (Fig. 5c, d). Additionally, there are very scarce *Heliosphaeridium dissimilare* (Fig. 6e, f) in levels transitional between the Lower and Upper members (Fig. 2).

All identified acritarch species have their first appearances in the *Skiagia–Fimbriaglomerella* Zone (Moczydłowska, 1991, fig. 5) except for *H. dissimilare* which together with *S. ciliosa* defines the *Heliosphaeridium–Skiagia* Zone (Moczydłowska, 1991). However, *H. dissimilare* is a species with poor diagnostic characters and it has been reported both from the Terreneuvian (lower Cordubian) in Iberia (Central Iberian Zone, Díez Balda & Fournier Vinas, 1981; Vidal *et al.* 1994) and Series 2 (Ovetian) in the *Skiagia–Fimbriaglomerella* Zone (Palacios & Vidal, 1992) in the Cantabrian Zone, much lower than the first

appearance of *S. ciliosa* and the first trilobite record (Fig. 11). In Tarim and South China, the *Asteridium–Heliosphaeridium–Comasphaeridium* acritarch assemblage has a comparable stratigraphic position to the *Asteridium–Comasphaeridium* Zone (Ahn & Zhu, 2017). This indicates that regionally *H. dissimilare* occurs much earlier than *S. ciliosa*, and that the latter is the more diagnostic zonal fossil. Although a few *Heliosphaeridium* species were present already in Cambrian Stage 2, significant diversification of the genus occurred later, around Cambrian Stage 3.

The *Skiagia–Fimbriaglomerella* Zone represents globally the greatest increase in diversity of Cambrian acritarchs (Vidal & Moczydłowska-Vidal, 1997) and the beginning of the Palaeozoic phytoplankton radiation (Palacios *et al.* 2018) close to the first appearance of trilobites. This event, well documented in the fossil record, has been proposed to define the base of the Cambrian Series 2 (Moczydłowska & Zang, 2006) and has been used as such by several authors (Moczydłowska, 2011; Rushton & Molyneux, 2011; Palacios *et al.* 2011, 2018). Landing *et al.* (2013, fig. 4) and Zhang *et al*. (2017, fig. 3) considered this zone diachronic, with an appearance in Avalonia that predates trilobites (Stage 2). This argument was based on a reinterpretation of the data on organic-walled microfossils that Palacios *et al.* (2011) presented from sections in New Brunswick. Landing *et al*. (2013) assigned the 530 Ma ash layer from the Somerset Street section to the *Skiagia–Fimbriaglomerella* Zone in the Hanford Brook section, where it is associated with a shelly fauna that Landing attributed to the sub-trilobitic *Watsonella crosbyi* Zone. However, Palacios *et al*. (2011, fig. 7), based on the succession of acritarchs in these two sections, advocated a different correlation between these two sections, in which the 530 Ma ash predates the *Skiagia–Fimbriaglomerella* Zone acritarchs.

The same succession of acritarch assemblages that was recognized in New Brunswick (*Asteridum–Comasphaeridium*; *Skiagia–Fimbriaglomerella*) is recognized also in Newfoundland (Palacios *et al.* 2018), where the sub-trilobitic *Watsonella crosbyi* Zone predates both the *Asteridium–Comasphaeridium* (*sensu* Palacios *et al*. 2018) and *Skiagia–Fimbriaglomerella* zones.

Acritarch data from the Terreneuvian–Cambrian Series 2 on the Digermulen Peninsula show a similar succession with acritarchs of the *Asteridium–Comasphaeridium* Zone in the Lower Breidvika Member (Fig. 7) (Högström *et al*. 2013). The absence of acritarch data from the Upper Breidvika Member and lowermost part of the Duolbagáisá Formation does not exclude a lower range of the *Skiagia–Fimbriaglomerella* Zone.

In Iberia (Fig. 11), acritarchs diagnostic of the *Skiagia–Fimbriaglomerella* Zone appear in the Herrería Formation with Ovetian (Cambrian Series 2) trilobites (Jensen *et al.* 2010; Liñán *et al.* 2015). In central Iberia (Central Ibérian Zone), the first trilobites are located in the upper part of the Pusa Formation overlying levels that contain a *Scenella*-like mollusc and acritarchs of the *Asteridium–Comasphaeridium* Zone (Fig. 11).

There are no data indicating that the appearance of *Skiagia–Fimbriaglomerella* Zone acritarchs occurs much earlier than the first appearance of trilobites. On the other hand, if it is accepted that the first appearance of trilobites is diachronic and strongly facies dependent (Zhang *et al.* 2017) it is inconsistent to use them as calibration of the *Skiagia–Fimbriaglomerella* Zone; we need an independent means of calibration in successions with good stratigraphic control. A clear example of this situation is given in Spain (Central Iberian Zone) where controversy arose from finding trilobites and archaeocyathids in the Pusa Formation (Jensen *et al.* 2010) at levels that had been classically attributed to the lower Cordubian correlated with the Fortunian (Liñán *et al.* 2002).

The first appearances of trilobites and *Skiagia* assemblages may not coincide (Zhang *et al*. 2017), however the latter, being cosmopolitan and less facies dependent, is more likely to represent an isochronous event, which we consider a solid candidate to define the base of Cambrian Series 2 (cf. Moczydłowska & Zang, 2006).

4.b. Heliosphaeridium dissimilare–Skiagia ciliosa Zone

The middle part of the Upper Member of the Duolbagáisá Formation includes a thick mudstone/siltstone interval with a good record of acritarchs in its upper half (Fig. 3). The first levels include the first appearance of very abundant *Skiagia ciliosa* (Fig. 7a-f) while rare *Globosphaeridium cerinum* (Fig. 6a, b), *Parmasphaeridium implicatum* (Fig. 6c, d), and *Heliosphaeridium obscurum* (Fig. 6g, h) appear close to levels with the olenelloid trilobites *Kjerulfia* n. sp. and *Elliptocephalus* n. sp. (Ebbestad *et al*. 2017, 2018).

Moczydłowska (1991) defined the *H. dissimilare–S. ciliosa* Zone by the First Appearance Datum (FAD) of both species. However, given the occurrence of *H. dissimilare* at much lower stratigraphic levels than the first appearance of *S. ciliosa* (discussed earlier) we consider *Skiagia ciliosa* to be the more diagnostic form. Other cosmopolitan and highly diagnostic species such as *Parmasphaeridium implicatum* (Fridrichsone) Jachowicz-Zdanowska, 2013 (Fig. 6c, d) and *Globosphaeridium cerinum* have their first appearances in this zone (Moczydłowska, 1991).

Skiagia ciliosa shows diagnostic morphological features that allow easy identification, although it also has the highest morphological variability among species of *Skiagia*. The original diagnosis of *Baltisphaeridium ciliosum* given by Volkova (1969, p. 260) included ‘central body is dark, compact, translucent’, morphological features also listed by Downie (1982, table 1). Later revisions by Moczydłowska (1991, p. 66, plate 7, A, B, D, F), included new characters: ‘bases of the processes are conical’ and ‘separated from the central body cavity by a plug’. In well-preserved material from New Brunswick (Palacios *et al.* 2017a, figs. 5a–c, 8a–d) and in specimens studied here (Fig. 7a–f), the conical

base of the process (Fig. 7a–d) is seen to have a thick and resistant wall, whereas the tubular part of the process (Figs 7a, b, 8a–c), separated by the plug, is thinner and more delicate. The transition to the plug is an area of weakness where the process regularly breaks (Figs 7b, 8c, e, f). This variability in preservation is a result of the development of the dark internal body and the thickening of the wall, which favours a preservation of the vesicle with the conical bases and the loss of the tubular part of the delicate processes (Fig. 8c, e, f). The tubular part of the processes exhibits certain variability (Moczydłowska, 1991) and does not constitute the most diagnostic character of *S. ciliosa*. The *Skiagia*-plexus concept of Moczydłowska (2010) has introduced certain confusion (Zhang *et al*. 2017, p. 135) in the identification of morphospecies of *Skiagia*, especially in *S. ciliosa*, by extending a very specific morphological feature of this species (the dark internal body–a suggested endocyst) to all species of the plexus as part of a life cycle of the cyst. The presence of a dark internal body in *Skiagia* has been clearly identified in species that appear in the *Heliosphaeridium–Skiagia Zone*. Species that have their FAD in the *Skiagia–Fimbriaglomerella* Zone, such as *S. orbiculare*, *S. compressa* and *S*. *ornata*, lack the internal body. Moczydłowska (2010, p. 132) placed *Baltisphaeridium bimacerium*, a species with a dark nucleus that appears in the *Heliosphaeridum–Skiagia* Zone (Zang, Moczydłowska & Jago, 2007, fig. 8), in synonymy of *S. ornata,* suggesting that it was ‘a mature stage’ while *S. ornata* was considered ‘an immature cyst’. If this is correct it would be necessary to justify the absence of the mature stage in the abundant and diverse associations of *Skiagia*, older than *S. ciliosa*, described in numerous assemblages. We do not think the interpretation by Moczydłowska (2010) is tenable, and therefore consider *Skiagia* species to be morphospecies that have been recorded in well-exposed sections with good stratigraphic control. Using this criterion, we have established the correlations shown in Figure 11, with areas of Avalonia and Iberia in which there is a good control on the first appearances of the *S. ciliosa* morphospecies. Some species attributed to *S. ciliosa*, such as those from the middle-upper Tommotian to lower Atdabanian stages of Siberia (Vidal, Moczydłowska & Rudavskaya*,* 1995*,* fig. 7, 3, 4; see Grazhdankin *et al.* 2020 for discussion on age) do not show the diagnostic features of *S. ciliosa* discussed above and their assignment should be reviewed.

4.c. Volkovia dentifera–Liepaina plana Zone

The upper portion of the siltstone-rich interval in the upper part of the Upper Member of the Duolbagáisá Formation records the first appearance of *Liepaina plana* (Fig. 9a), *Heliosphaeridium notatum* (Fig. 6i) and *Retisphaeridium dichamerum* (Fig. 9c), a few meters above the trilobite occurrences (Fig. 3).

L. plana and *H. notatum* have a cosmopolitan distribution and their first appearances indicate the *Volkovia–Liepaina* Zone. However, *L. plana* is a very rare species in Cambrian Stage 4 rocks in Baltica, and its maximum abundance is recorded in the Miaolingian, equivalent to the *Acadoparadoxides oelandicus*

Zone (Volkova *et al.* 1983). A similar situation occurs in New Brunswick (Palacios *et al.* 2017a), and is also observed in the study area, with maximum abundance of *Liepaina plana* in the lower part of the Kistedalen Formation (Fig. 3; Fig. 9b). *Heliosphaeridium notatum*, a diagnostic species of the *Volkovia–Liepaina* Zone, is more abundant than *L. plana* and with a global distribution, and therefore more useful for correlation. For a detailed discussion on the distribution of *L. plana* and *H. notatum* we refer to Palacios *et al.* (2017a). *R. dichamerum,* first found in the Miaolingian *Albertella* Zone of Alberta, Canada, (Staplin *et al.* 1965), has a cosmopolitan distribution with reports from Laurentia, Baltica, Gondwana and the peri-Gondwanan terrains of Avalonia, Ganderia and Iberia (Downie, 1982; Martin & Dean, 1988; Vidal & Peel, 1993; Molyneux *et al.* 1996; Rushton & Molyneux, 2011; Palacios *et al.* 2012, 2017a; Palacios, 2015). Identification of *R. dichamerum* can be difficult as flattened specimens may be confused with *Cymatiosphaera* or flattened *Leiosphaeridia*, because the diagnostic character that allows its easy identification is the rupture of the vesicle into plates (Downie, 1982, fig. 11p; Palacios, 2015; Palacios *et al*. 2017a). The rupture into plates is a morphological feature of Miaolingian acritarchs similar to some modern dinoflagellates, and it marks the important evolutionary innovation of 'placoid acritarchs'. These include some of the most diagnostic genera of the Miaolingian and Furongian, such as *Eliasum*, *Cristallinium*, *Timofeevia*, *Vulcanisphaera* and *Stelliferidium* (Palacios *et al.* 2009, 2017a; Palacios, 2015). *Retispheridium dichamerum* has been reported from the *Heliosphaeridium–Skiagia Zone* (Eklund, 1990; Hagenfeldt, 1989; Vidal & Peel, 1993), and is clearly present at higher levels (upper Series 2) in Scotland (Downie, 1982, fig. 11p) and Newfoundland. In Newfoundland, *R. dichamerum* is abundant in the highest Cambrian Series 2, Brigus Formation (*Catadoxides* Zone of Howell 1925), and the *Triplagnostus gibbus* Zone of the lowest part of the Chamberlains Brook Formation (Martin & Dean, 1983, 1984, 1988).

In our opinion, *R. dichamerum* is a diagnostic species whose first appearance is close to that of the species defining the base of the *Volkovia–Liepaina* Zone. As with *L. plana*, the maximum abundance of *R. dichamerum* is in the Wuliuan Stage. This trend is clearly observed on the Digermulen Peninsula (Fig. 3).

Proposed correlations of the *Volkovia–Liepaina* Zone are shown in Figure 11.

5. Cambrian Series 2–Miaolingian transition assemblages and the Hawke Bay regression

The upper levels of the Upper Member of the Duolbagáisá Formation, dominated by quartzitic sandstone with scarce siltstone, record the last occurrence of *Skiagia* (Fig. 3). At this level, there is a low diversity assemblage dominated by abundant *Leiosphaeridia* spp. and rare acritarchs indicative of the *Volkovia–Liepaina* Zone. The transition between Cambrian Stage 4 and the Wuliuan Stage marks a significant decrease in the diversity of acritarchs, well

documented in continuous sections without a significant hiatus. The disappearance of *Skiagia* species in the upper Cambrian Stage 4 has been verified in different continuous and well-exposed sections of Avalonia (Palacios *et al.* 2017a), Iberia (Palacios, Jensen & Apalategui, 2006), and in the Brunovistulicum terrain (Jachowicz-Zdanowska, 2013), while possible redeposition in the *oelandicus* beds of Baltica has been suggested (Jachowicz-Zdanowska, 2013, p. 15). A possible explanation for the presence of *Skiagia* in Miaolingian deposits may be reworking of Cambrian Series 2 acritarchs including the *Skiagia* assemblages dominated by *S. ciliosa* during the Hawke Bay regression at the Cambrian Stage 4–Wuliuan transition. Palynomorphs, such as acritarchs, commonly occur in great abundance and are especially sensitive to reworking because of their small size. Reworking may involve material of very different ages and result in well-preserved acritarchs, such as the reworked Ordovician acritarchs of the Barrancos Formation (Portugal) in Carboniferous continental strata that contain abundant spores (Lopes *et al*. 2014). In this case, the reworking is evidenced from known stratigraphical range, not from state or preservation. However, in material with similar diagenetic or metamorphic history and deposited in similar environments, recognition may be problematic.

Different studies show the presence of reworked palynomorphs in regressive series (Habib *et al*. 1994, p. 331; Stover *et al*. 1996, p. 706), and also show concentrations in the basal sequence of the new transgressive event above the boundary unconformity (Stover *et al*. 1996, p. 706). This model is applied in our hypothesis.

The Cambrian in Baltica includes a highly condensed series of poorly lithified sediments in several areas, that under lowstand sea level conditions would be easily remobilized. The pattern observed in sections with a good record of organic-walled microfossils in Baltica is 1) a great abundance of *Skiagia* (mainly *S. ciliosa*) in *Holmia* beds (*S. ciliosa–H. dissimilare* Zone, Moczydłowska, 1991), 2) a disappearance (Eklund, 1990) or a major decrease of Skiagia in the regressive series corresponding to the *Volkovia–Liepaina* Zone (Moczydłowska, 1991, Radzyn IG-1 and Łopiennik boreholes; Jankauskas, 2002, Kibartai-22 borehole), and 3) a reappearance of *Skiagia* (mainly *S. cilosa*) in the generally discordant transgressive series of *oelandicus* Beds (Volkova *et al.* 1983; Hagenfeldt, 1989; Eklund, 1990; Moczydłowska, 1991; Jankauskas, 2002). In our opinion, the most abundant forms having more resistant walls, such as *S. ciliosa,* will be the most prone to be remobilized and incorporated in Wuliuan sediments of the *oelandicus* Superzone (Moczydłowska, 1991, 1998), where they became mixed with typical Miaolingian assemblages, increasing the overall biodiversity. Another hypothesis to explain this trend is the reappearance of *Skiagia* in Miaolingian strata. However, observations of our study do not support this, and reworking is the most plausible hypothesis for the observed pattern. The presence of *Skiagia* in *oelandicus* beds therefore artificially modify patterns of biodiversity (cf. Vidal & Moczydłowska-Vidal, 1997; Nowak *et al.* 2015). Thus, the important extinction signal at the Cambrian Series 2–Miaolingian transition, marked by the disappearance of typical assemblages of Cambrian Series 2

dominated by *Skiagia,* and the diversification of the ‘placoid acritarchs’ that dominate the Miaolingian becomes distorted.

Sections with a good record of acritarchs in Baltica support this notion. Eklund (1990) described assemblages dominated by *Skiagia* in the Mickwitzia Sandstone Member (Assemblage B) of southern Sweden, followed by their disappearance in the Lingulid Sandstone Member in levels that contain *Volkovia dentífera* (Assemblage C), and their reappearance in the ‘Glauconite sandstone’ and *oelandicus* mudstone (Assemblage D), which are contemporary with the Wuliuan (Kibartai Stage). A similar situation occurs in northern Spain with the disappearance of *Skiagia* at the top of Huérmeda Formation and the reappearance of reworked *Skiagia* in the regressive Daroca Formation (Palacios & Moczydłowska, 1998). In comparison with material in the Huérmeda Formation *Skiagia* in the Daroca Formation are more poorly preserved and with broken processes.

It therefore appears probable that the presence or absence of reworked *Skiagia* in Miaolingian strata serves as an indicator of the intensity of the regressive events at the Stage 4–Wuliuan transition. It follows that the absence of *Skiagia* in the upper Duolbagáisá and Kistedalen formations indicates limited reworking. This is also consistent with the sedimentology and ichnology of these units. Marine conditions are indicated by the presence of trace fossils throughout the Duolbagáisá Formation with forms typical of the Skolithos and Cruziana ichnofacies (Banks, 1973), and by acritarchs in fine-grained interbeds. Deposition of thick sandstone beds in the upper member Duolbagaisa Formation was dominated by strong tidal currents in a shoreface to offshore setting (cf. Banks, 1973; Crimes & McIlroy, 1999). The lower member of the Kistedalen Formation similarly yields trace fossils and acritarchs. The Hawke Bay regression on the Digermulen Peninsula therefore is represented by shallow marine facies without evidence for an unconformity, which is consistent with an originally distal position of the area compared to units formed upon the craton (cf. Nielsen & Schovsbo, 2015, figs 12–15).

The appearance of a single specimen of *Comasphaeridum longispinosum* (Fig. 10b), an acritarch so far known only from the Miaolingian (Jachowicz-Zdanowska, 2013; Palacios *et al*. 2017a) at the top of the Duolbagáisá Formation suggests that the Cambrian Series 2–Miaolingian boundary is located close to the top of this unit (Fig. 3). The first siltstone levels of the K1 Member of the Kistedalen Formation yield a more diverse assemblage with abundant *Retisphaeridium dichamerum* (Fig. 9d), *C. longispinosum* (Fig. 10c) and *Liepaina plana* (Fig. 9, b), and the first appearance of *Multiplicisphaeridium llynense* (Fig. 9f; see revision of Jachowicz-Zdanowska, 2013) and *Eliasum llaniscum* (Fig. 10a) clearly diagnostic of the Miaolingian.

6. Conclusions

The Duolbagáisá Formation contains one of the more complete successions of acritarch assemblages of Cambrian Series 2. The Cambrian Series 2–Miaolingian acritarch associations indicate an essentially transitional record across this boundary.

Skiagia assemblages are limited to Cambrian Series 2 strata, following the same trends observed in the peri-Gondwanan terrains of Avalonia and Iberia, confirming the existence of an important acritarch extinction at the end of Cambrian Series 2.

Occurrences of *Skiagia* in Miaolingian strata of Baltica are interpreted as reworked material related to the Hawke Bay unconformity at the Cambrian Series 2–Miaolingian transition. The absence of reworked *Skiagia* in the Kistedalen Formation indicates that the Hawke Bay regression did not result in an unconformity in this area.

The base of the Wuliuan Stage is located in the uppermost part of the Duolbagáisá Formation, whereas the acritarch association from the lowermost part of K1 Member of the Kistedalen Formation contains taxa attributable to the Miaolingian Series.

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Figure captions

Fig. 1. Location and geological setting of study area on the Digermulen Peninsula, Arctic Norway. (a) Geographical location of the Digermulen Peninsula. (b) Geology of the Breidvika Valley area with location of the Duolbagáisá Formation sections of this study.

Fig. 2. Lithostratigraphic column of Siskkit Vuorrevággi coastal section north of Breidvika Valley (Lower Member of the Duolbagáisá Formation) showing location of samples and their sample number, occurrence and abundance of acritarch species in each slide.

Fig. 3. Lithostratigraphic column of the Breidvika Valley section (Upper Member of the Duolbagáisá Formation) showing location of samples and their sample number, occurrence and abundance of acritarch species. See Figure 2 for legend.

Fig. 4. Acritarchs from the Duolbagáisá Formation (Lower Member), Siskkit Vuorrevággi section. In this and the following figures are given the sample number, museum number, and England finder coordinates. Scale bar = 20 µm. **(a, b)** *Skiagia orbiculare* (Volkova) Downie. **(a)** P11-30, TSGf 18435, Q-33. **(b)** D14-72, TSGf 18438a, T-26-2. **(c)** *Skiagia brevispinosa* Downie, D14-70, TSGf 18437a, O-29. **(d, e)** *Skiagia ornata* (Volkova) Downie. **(d)** P11-31, TSGf 18436, K-33-3. **(e)** D14-72, TSGf 18438b, M-44-4. **(f, g)** *Skiagia compressa* (Volkova) Downie. **(f)** D14-72, TSGf 18438c, E-26-1-3. **(g)** D14-72, TSGf 18438d, C-38-3.

Fig. 5. Acritarchs from the Duolbagáisá Formation. Scale bar = 20 µm. **(a, b)** Lower Member, Siskkit Vuorrevággi section. **(b, c)** Upper Member, Breidvika Valley section. **(a)** *Fimbriaglomerella membranacea* (Kirjanov) Moczydłowska & Vidal, D14-72, TSGf 18438e, L-18-2. **(b)** *Comasphaeridium brachyspinosum* (Kirjanov) Moczydłowska & Vidal, D14-70, TSGf 18437b, W-17-1. **(c, d)** *Lophosphaeridium dubium* (Volkova) Moczydłowska. **(c)** D13-65, TSGf 18439a, D-17. (d) D13-65, TSGf 18439b, R-14-1-3.

Fig. 6. Acritarchs from the Duolbagáisá Formation (Upper Member), Breidvika Valley section. Scale bar = 20 µm. **(a, b)** *Globosphaeridium cerinum* (Volkova) Moczydłowska. **(a)** D13-110, TSGf 18441a, C-38-4. **(b)** D13-109, TSGf 18440a, E-25-1 **(c, d)** *Parmasphaeridium implicatum* (Fridrichsone) Jachowicz-Zdanowska. **(c)** P11-49, TSGf 18443a, B-18-1-2. **(d)** D13-113, TSGf 18444a, R-40-4. **(e, f)** *Heliosphaeridium dissimilare* (Volkova) Moczydłowska. **(e)** D13-110, TSGf 18442a, E-45. **(f)** P11-49, TSGf 18443b, Q-22-2. **(g, h)** *Heliosphaeridium obscurum* (Volkova) Moczydłowska. **(g)** D13-110, TSGf 18442b, A-19-2. **(h)** D13-110, TSGf 18441b, A-26-2. **(i)** *Heliosphaeridium notatum* (Volkova) Moczydłowska, D13-113, TSGf 18444b, C-17-1.

Fig. 7. Acritarchs from the Duolbagáisá Formation (Upper Member), Breidvika Valley section. Scale bar is equivalent to 20 µm. **(a–f)** *Skiagia ciliosa* (Volkova) Downie. In the Figures 7 and 8, the arrows show the clear and distinctive plug (p), conical base (c) and some broken (br) processes. **(a)** D13-109, TSGf 18440b, L-38-1. **(b)** D13-113, TSGf 18444c, U-37-4. **(c)** D13-109, TSGf 18440c, B-33-4. **(d)** D13-109, TSGf 18440d, D-34-1-2. **(e)** Specimen with a dark internal body (a possible endocyst) D13-110, TSGf 18441c, E-20-2. **(f)** Specimen with dark internal body D13-3, TSGf 18445, H-17-2-4

Fig. 8. *Skiagia ciliosa* from Avalonia. Scale bar is equivalent to 20 µm. **(a–c)** New Brunswick, St. Martins Member, Hanford Brook Formation. **(e)** Newfoundland, Brigus Formation, Dantzig Cove section. **(d, f)** Iberian Peninsula. **(d)** Cantabrian Zone, Lower Member, Lancara Formation. **(f)** Ossa Morena Zone, Lower Member, Vallehondo Formation. **(a)** Hanf09-3, slide 2, B-24. **(b)** Specimen with dark internal body, Hanf09-3, slide 2, H-27-2. **(c)** Specimen with broken processes, Hanf09-3, slide 2, B-46-2. **(d)** BL14-1, slide 1, C-20. **(e)** Specimen with broken processes, DC17-12, slide 2, T-16-3. **(f)** Specimen with broken processes, CA06-4, slide 1, C-44-1.

Fig. 9. Acritarchs from the Upper Member of the Duolbagáisá Formation **(a, c, e)** and K1 Member of the Kistedalen Formation **(b, d, f)**, all Breidvika Valley section. **(a, b)** *Liepaina plana* Jankauskas & Volkova. **(a)** D13-109, 18440e, L-42. **(b)** D14-87, TSGf 18447a, E-16-3. **(c, d)** *Retisphaeridium dichamerum* Staplin, Jansonius & Pocock. **(c)** D13-109, TSGf 18440f, D-24-3-4. **(d)** D14-87, TSGf 18447b, D-32-3. **(e)** *Sagatum priscum* (Kirjanov & Volkova) Vavrdová & Bek, D13-94, TSGf 18446a, B-22-4. **(f)** *Multiplicisphaeridium llynense* (Martin) Jachowicz-Zdanowska, D14-87, TSGf 18447c, N-28. Scale bar = 20 µm.

Fig. 10. Acritarchs from the Upper Member of the Duolbagáisá Formation **(b),** and K1 Member of the Kistedalen Formation **(a, c**), all Breidvika Valley section. **(a)** *Eliasum llaniscum* Fombella, D14-87, TSGf 18447a, Q-45-1. **(b, c)** *Comasphaeridium longispinosum* Hagenfeldt. **(b)** D13-94, TSGf 18446b, J-46-1. **(c)** D14-87, TSGf 18447e, M-34. Scale bar = 20 µm.

Fig. 11. Acritarch-based correlation chart of the Cambrian Terreneuvian–Miaolingian (Wuliuan) of the Digermulen Peninsula, Avalonia (New Brunswick and Newfoundland) and Iberia. Sources: New Brunswick – Palacios *et al*. (2011, 2017a); Newfoundland – Palacios *et al*. (2016, 2018) for Chapel Island, Random and Brigus (lower part) formations and Martin & Dean (1983) for the upper part of the Brigus and Chamberlain Brooks formations; Cantabrian Zone, northern Spain – Palacios (2015), Palacios & Vidal (1992). Palacios et al. (2014) and Palacios unpublished data); Iberian Chains, northern Spain – Palacios & Moczydłowska (1998); Central Iberian Zone, central Spain – Jensen *et al.* (2010). Ossa-Morena Zone, southern Spain – Palacios *et al.* (2006), and Palacios unpublished data).

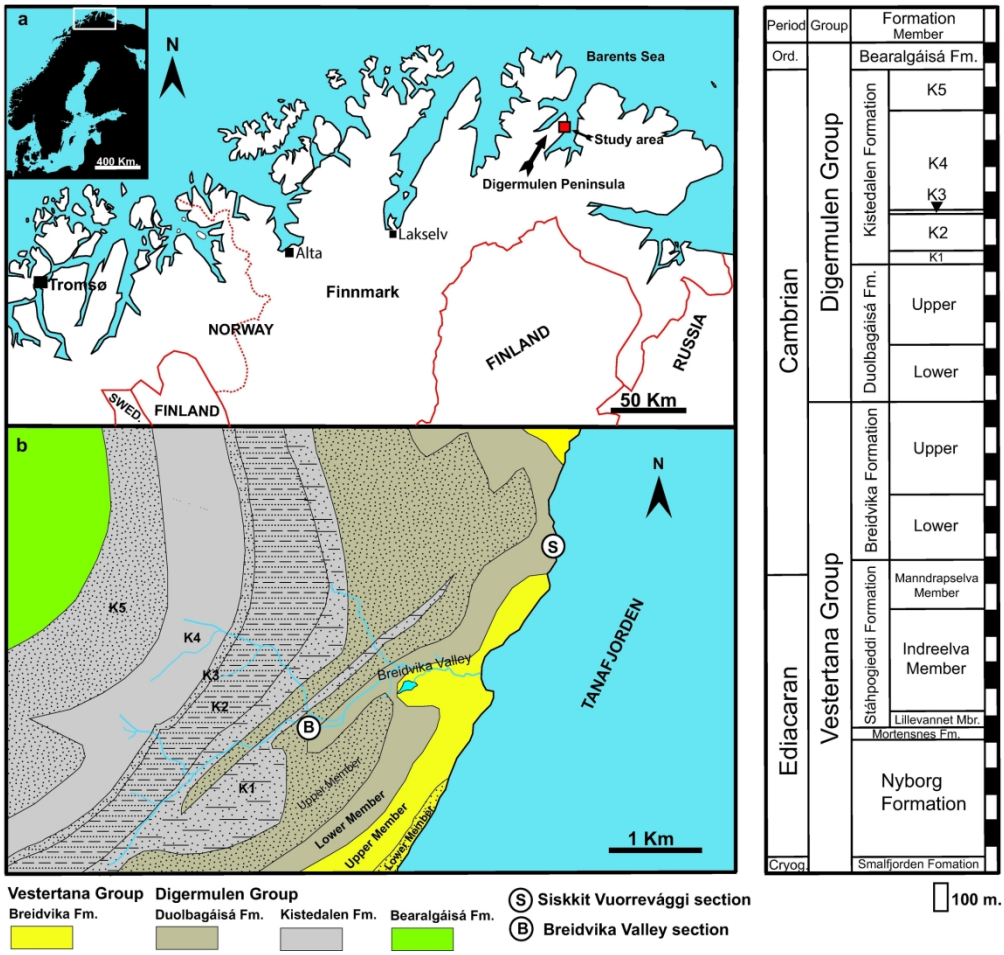
a
N
400 Km.
Barents Sea
Study area
Digermulen Peninsula
Alta
Lakselv
Tromsø
Finnmark
NORWAY
FINLAND
RUSSIA
SWED.
FINLAND
50 Km
b
N
K5
K4
K3
K2
K1
Breidvika Valley
TANAFJORDEN
Upper Member
Lower Member
Upper Member
Lower Member
1 Km
Vestertana Group
Breidvika Fm.
Digermulen Group
Duolbagáisá Fm.
Kistedalen Fm.
Bearalgáisá Fm.
S Siskkit Vuorrevággi section
B Breidvika Valley section
Period
Group
Formation
Member
Ord.
Cambrian
Ediacaran
Cryog.
Digermulen Group
Vestertana Group
Bearalgáisá Fm.
Kistedalen Formation
K5
K4
K3
K2
K1
Duolbagáisá Fm.
Upper
Lower
Breidvika Formation
Upper
Lower
Stáhpogieddi Formation
Manndrapselva Member
Indreelva Member
Lillevannet Mbr.
Mortensnes Fm.
Nyborg Formation
Smalfjorden Fomation
100 m.

Figure 1

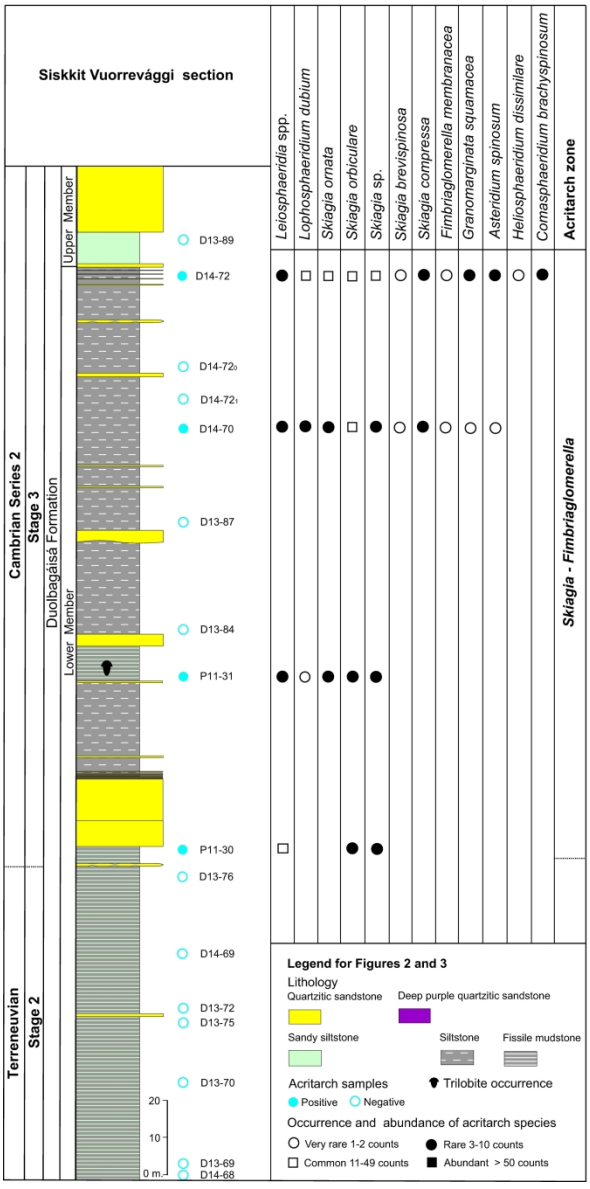
Siskkit Vuorrevággi section
Cambrian Series 2
Stage 3
Duolbagáisá Formation
Upper Member
Lower Member
Stage 2
Terreneuvian
D13-89
D14-72
D14-72₀
D14-72₁
D14-70
D13-87
D13-84
P11-31
P11-30
D13-76
D14-69
D13-72
D13-75
D13-70
D13-69
D14-68
20
10
0 m
Leiosphaeridia spp.
Lophosphaeridium dubium
Skiagia ornata
Skiagia orbiculare
Skiagia sp.
Skiagia brevispinosa
Skiagia compressa
Fimbriaglomerella membranacea
Granomarginata squamacea
Asteridium spinosum
Heliosphaeridium dissimilare
Comasphaeridium brachyspinosum
Acritarch zone
Skiagia - Fimbriaglomerella
Legend for Figures 2 and 3
Lithology
Quartzitic sandstone
Deep purple quartzitic sandstone
Sandy siltstone
Siltstone
Fissile mudstone
Acritarch samples
Trilobite occurrence
Positive
Negative
Occurrence and abundance of acritarch species
Very rare 1-2 counts
Rare 3-10 counts
Common 11-49 counts
Abundant > 50 counts

Figure 2

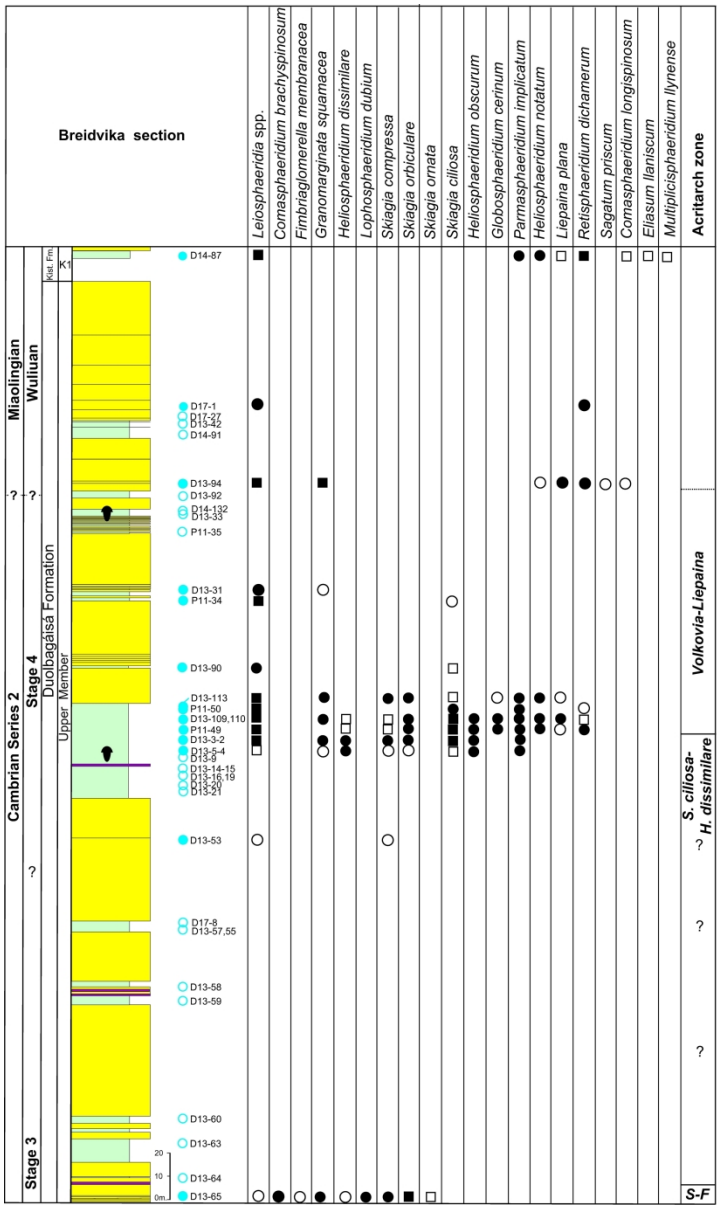
Breidvika section
Cambrian Series 2
Miaolingian
Stage 3
Stage 4
Wuliuan
Duolbagáisá Formation
Upper Member
Kist. Fm.
K1
D14-87
D17-1
D17-27
D13-42
D14-91
D13-94
D13-92
D14-132
D13-33
P11-35
D13-31
P11-34
D13-90
D13-113
P11-50
D13-109,110
P11-49
D13-3-2
D13-5-4
D13-9
D13-14-15
D13-16,19
D13-20
D13-21
D13-53
D17-8
D13-57,55
D13-58
D13-59
D13-60
D13-63
D13-64
D13-65
20
10
0m
Leiosphaeridia spp.
Comasphaeridium brachyspinosum
Fimbriaglomerella membranacea
Granomarginata squamacea
Heliosphaeridium dissimilare
Lophosphaeridium dubium
Skiagia compressa
Skiagia orbiculare
Skiagia ornata
Skiagia ciliosa
Heliosphaeridium obscurum
Globosphaeridium cerinum
Parmasphaeridium implicatum
Heliosphaeridium notatum
Liepaina plana
Retisphaeridium dichamerum
Sagatum priscum
Comasphaeridium longispinosum
Eliasum llaniscum
Multiplicisphaeridium llynense
S-F
S. ciliosa-
H. dissimilare
Volkovia-Liepaina
Acritarch zone

Figure 3

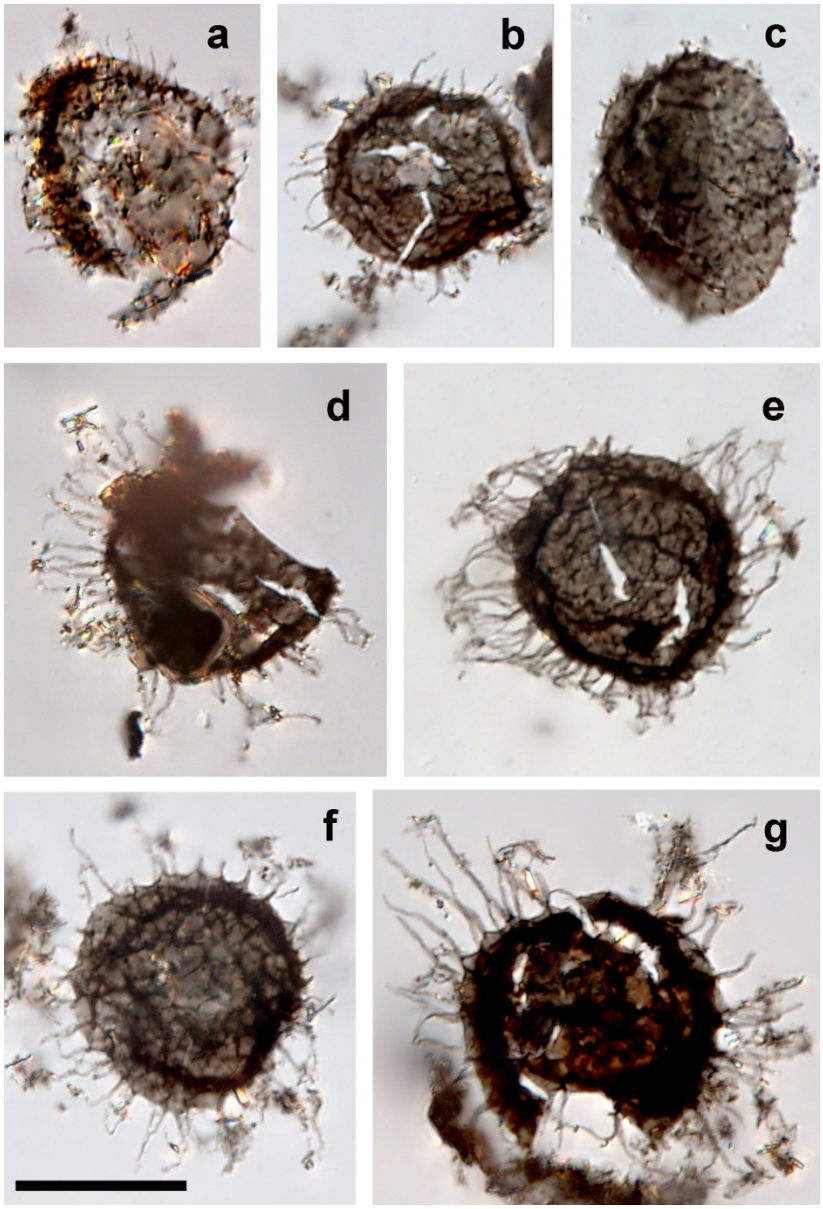

Figure 4

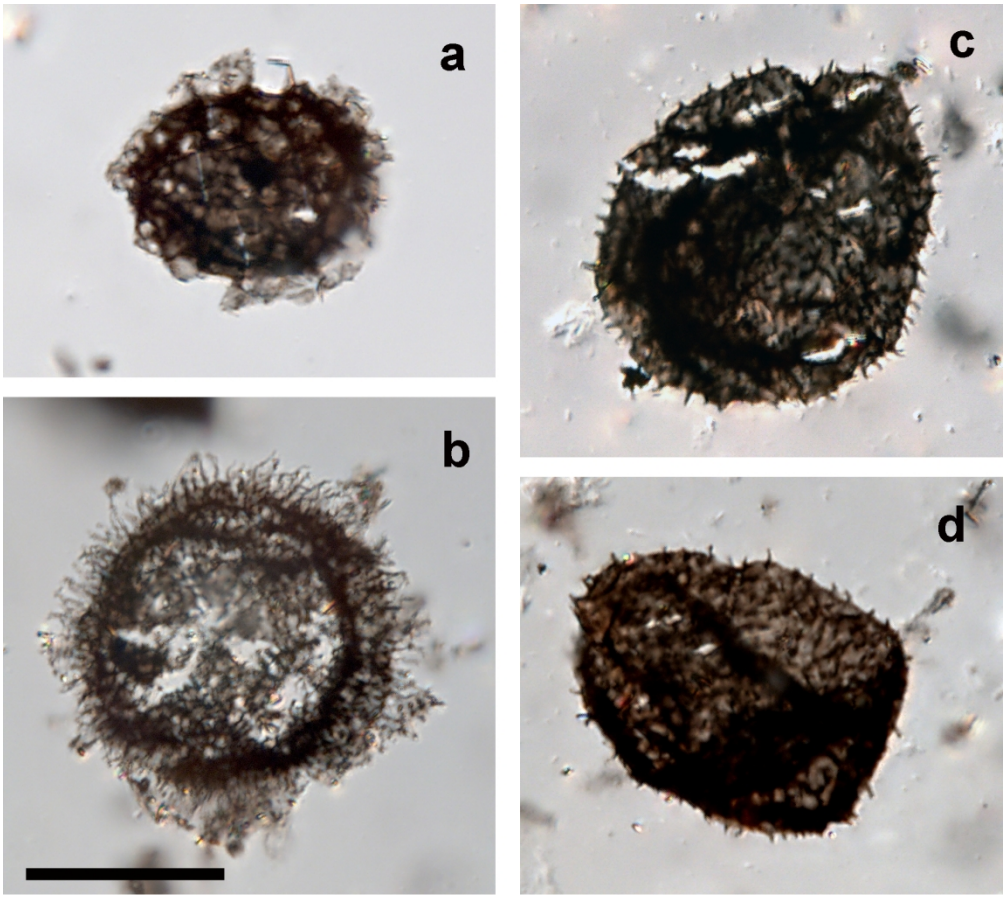

Figure 5

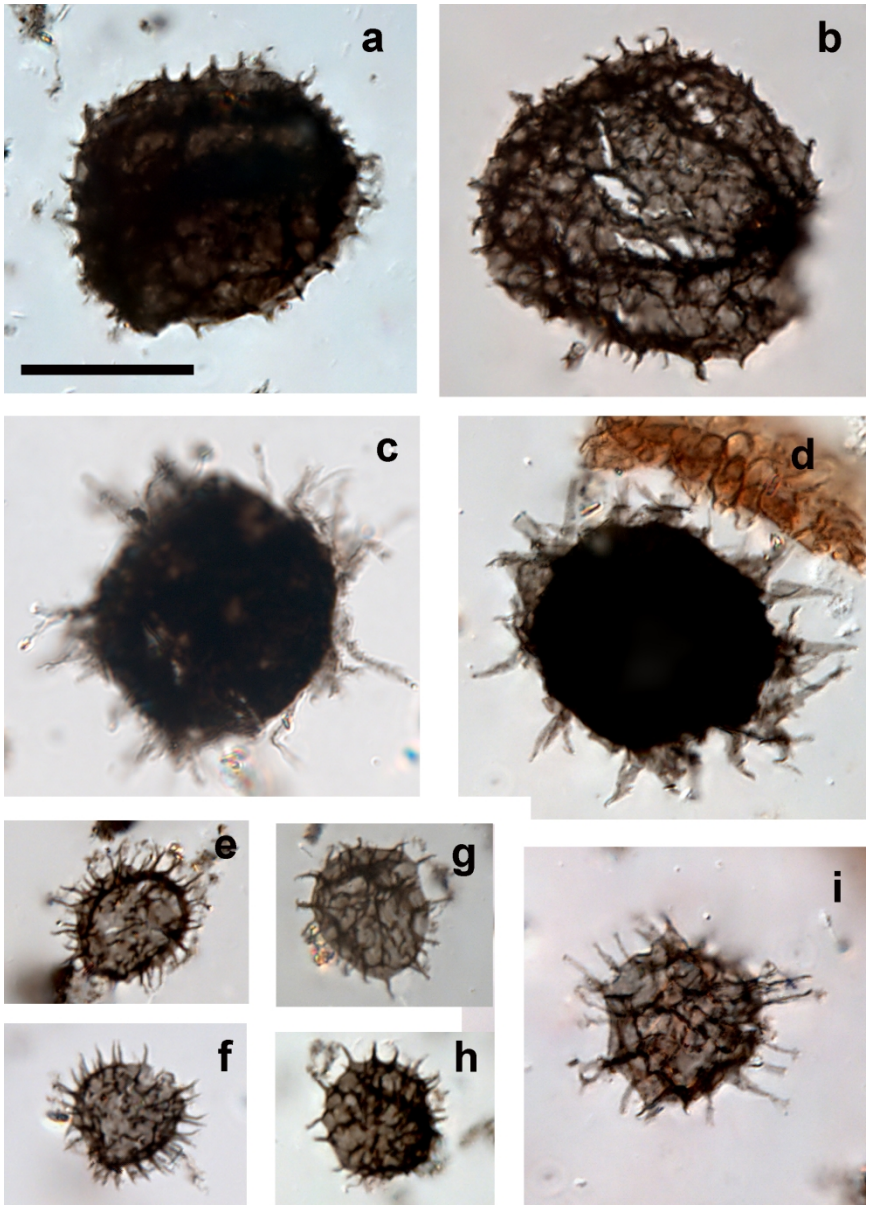

Figure 6

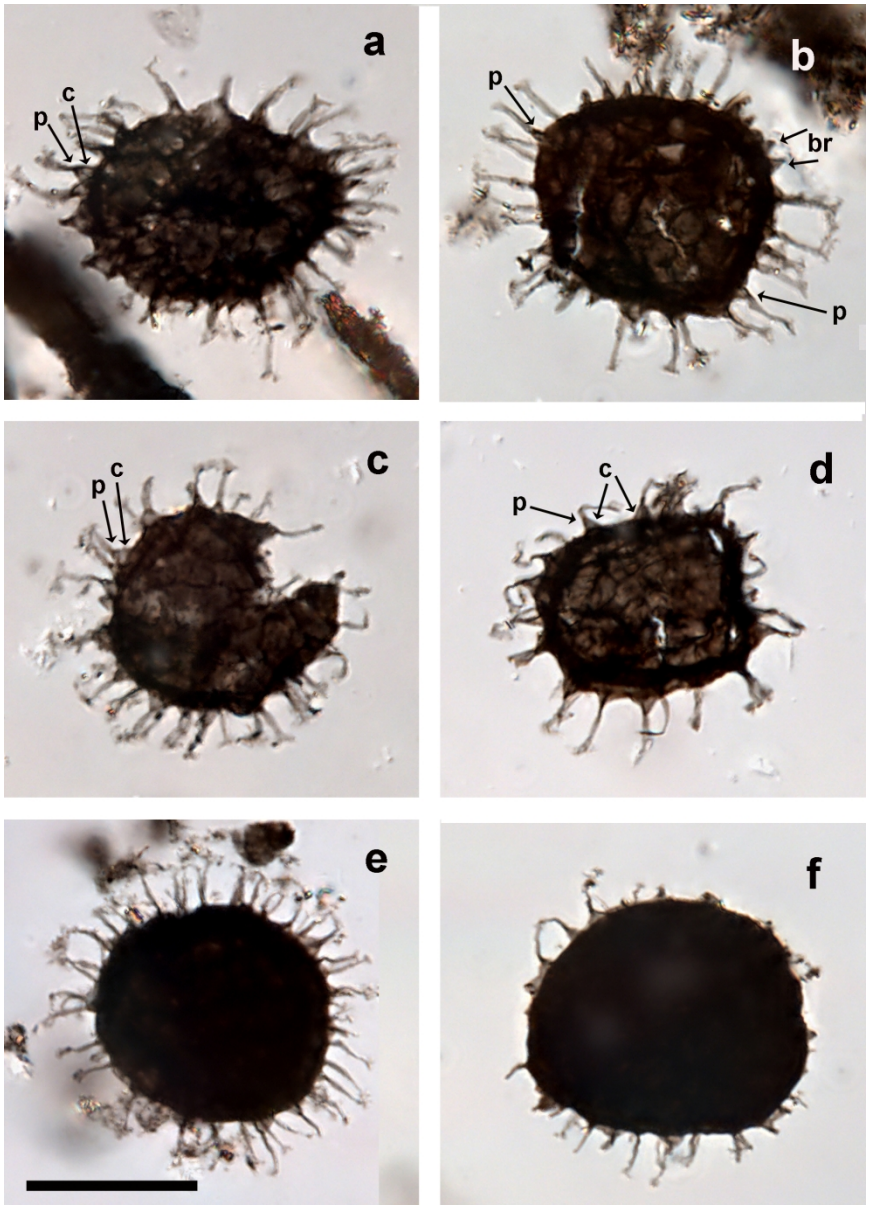

Figure 7

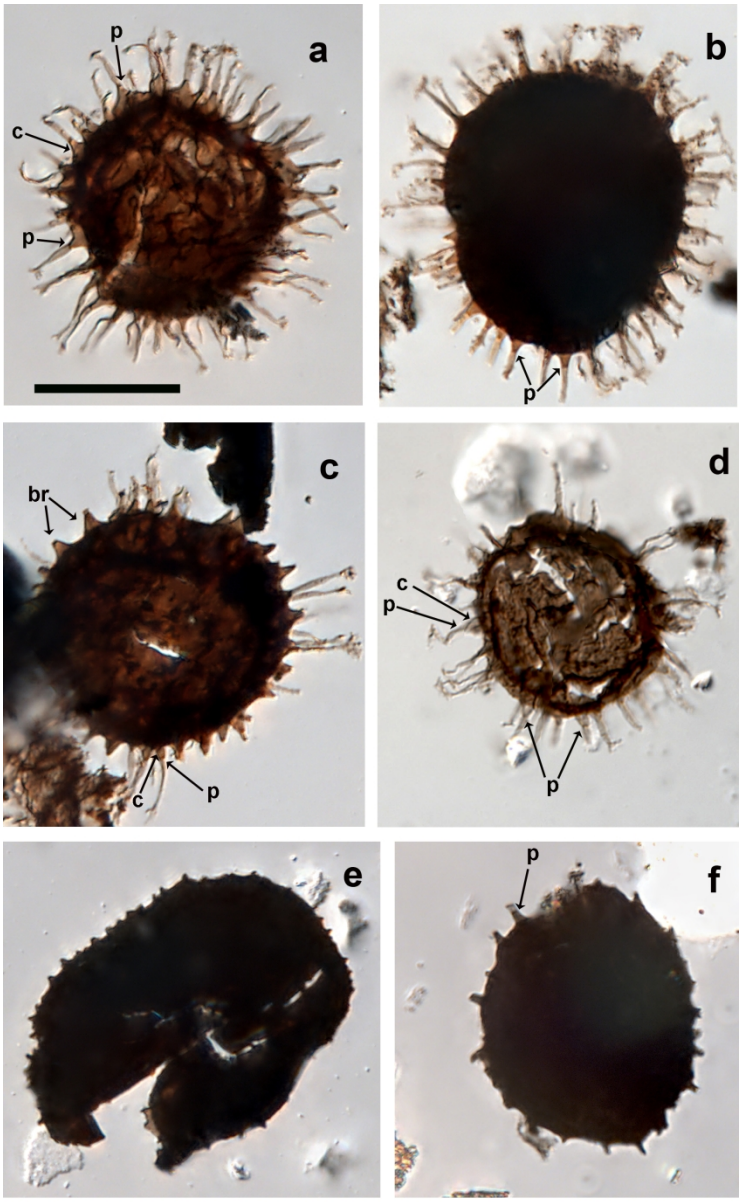

Figure 8

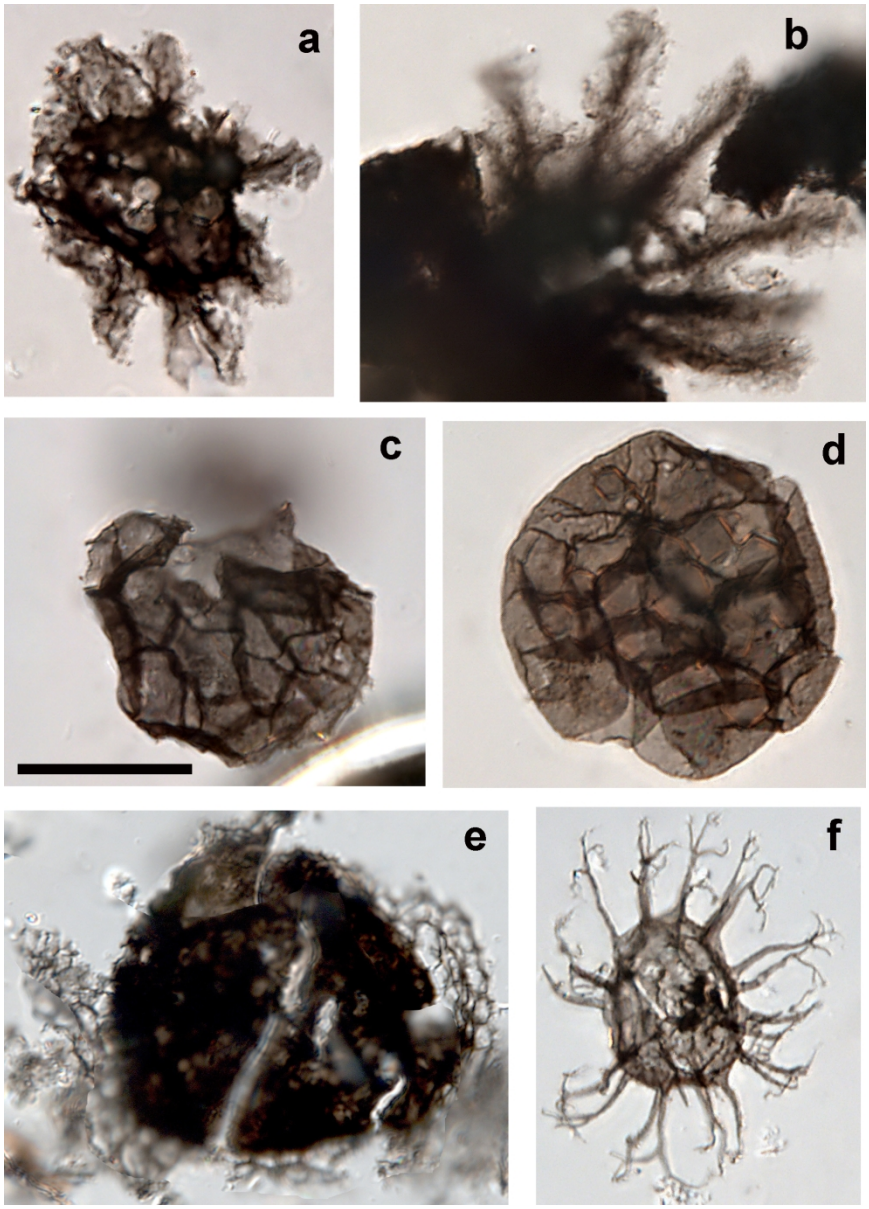

Figure 9

Figure 10

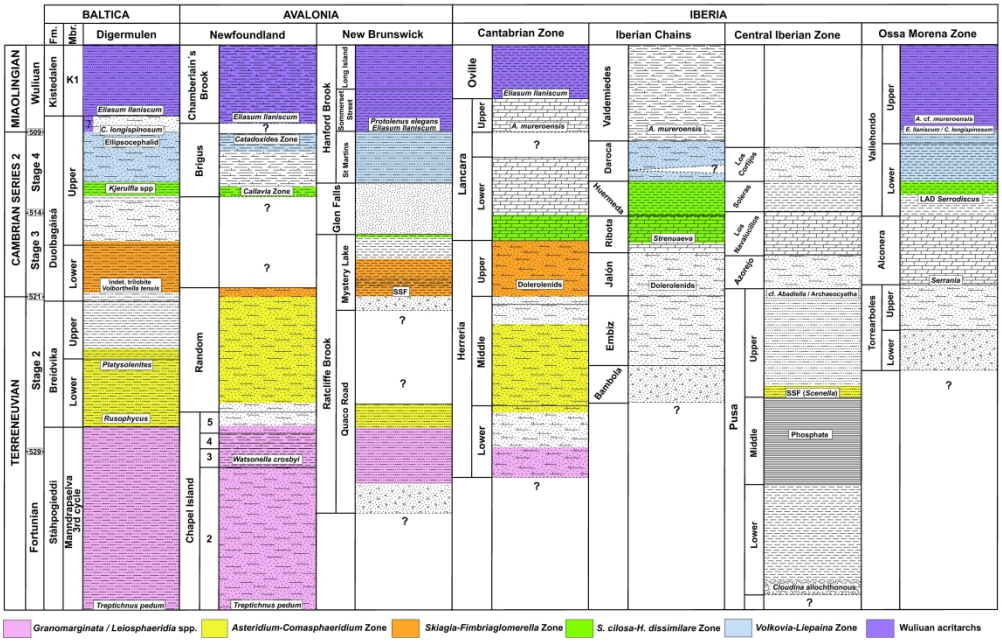
BALTICA
AVALONIA
IBERIA
Digermulen
Newfoundland
New Brunswick
Cantabrian Zone
Iberian Chains
Central Iberian Zone
Ossa Morena Zone
MIAOLINGIAN
CAMBRIAN SERIES 2
TERRENEUVIAN
Wuliuan
Stage 4
Stage 3
Stage 2
Fortunian
Kistedalen
Duolobagåsa
Breivika
Stahpogieddi
Mannrapselva
Jas Canada
Upper
Lower
Middle
Eliasum llaniscum
C. longispinosum
Ellipsocephalid
Kjerulfia spp
Indet. trilobite
Volborthella tenuis
Platysolenites
Rusophycus
Treptichnus pedum
Chamberlain's Brook
Brigus
Random
Chapel Island
Callavia Zone
Catadoxides Zone
Watsonella crosbyi
Hanford Brook
Glen Falls
Mystery Lake
Ratcliffe Brook
Quaco Road
Protolenus elegans
SSF
Oville
Lancara
Herrería
A. mureroensis
Dolerolenids
Valdemiedes
Daroca
Huermeda
Ribota
Jalón
Embiz
Bambola
Strenuaeva
Los Cortijos
Salares
Los Monolitos
Azorejo
Pusa
cf. Abadiella / Archaeocyatha
SSF (Scenella)
Phosphate
Cloudina allochthonous
Valdehondo
Alconera
Torrearboles
A. cf. mureroensis
E. llaniscum / C. longispinosum
LAD Serrodiscus
Serrania
Granomarginata / Leiosphaeridia spp.
Asteridium-Comasphaeridium Zone
Skiagia-Fimbriaglomerella Zone
S. cilosa-H. dissimilare Zone
Volkovia-Liepaina Zone
Wuliuan acritarchs

Figure 11